Inorganic Stabilisation Methods for Extruded Earth Masonry Units

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Abstract

Addressing the challenges of embodied environmental impact of materials has led to growing interest in the use of earth as a construction material. Adopting large-scale commercial methods of extruded brick production has potential to overcome many of the existing barriers of adoption. Without the firing the bricks will have a significantly lower embodied environmental impact and similar dimensions (just over 100mm thick in the UK) to conventional masonry. However, the wider adoption of 100mm thick unfired earth masonry is dependent on its suitability for use in structurally load-bearing applications. Currently the greatest barrier to earth masonry adoption is the durability of the material when subjected to high moisture contents. Accidental or intentional wetting of a 100mm thick load bearing unfired earth wall could lead to disproportionate collapse unless the moisture resistance is improved.

To overcome the concern of elevated moisture contents, a common approach is to chemically stabilise the soil using either cement or lime. While there has been research into the use of cement and lime for other forms of earth construction, their use for extruded earth bricks has not been investigated in depth. The source materials and inherent physical properties of extruded earth bricks are different to other forms of earthen construction. Therefore the suitability of cement and lime to stabilise soil for the purpose of extruded earth bricks requires investigation.

This research demonstrates the improvement in 28 day compressive strength, with a range of cement or lime contents and three initial curing temperatures. Small scale bricks were tested in both the ambient environmental conditions and following 24 hours of full submersion in water. Key factors, such as density and moisture content, are shown to be important for compressive strength development. The effect of stabilisation has been shown to be more important as a determinant for strength than density and moisture content alone.

1 Introduction

Earthen construction has been used for thousands of years, but only relatively recently has there been a focus on quantifying and understanding the engineering properties for potential structural applications (Heath et al., 2012). The interest of earthen construction methods is largely due to concerns of embodied carbon of construction materials. Meeting structural requirements, while using existing methods of construction, requires development and innovation with earthen materials and techniques.

1.1 Unstabilised earth masonry

Heath et al. (2009) investigated the properties of 12 different commercially produced unfired clay bricks, provided by different manufacturers in the UK. The bricks were produced using the same process that is used for large scale fired brick production, however without the use of the kiln for firing. Heath et al. (2012) presented the feasibility of using these unfired clay bricks as a replacement for concrete blocks for some domestic buildings, demonstrating the structural capacity of the units, however there were concerns about water resistance.

The greatest single barrier to unfired earthen construction is the low strength of the material when subject to high moisture contents. While this can be considered as an accidental case, the structural use of 100mm thick unfired unstabilised earth units is currently not recommended because of the danger of disproportionate collapse. The potential for disproportional collapse has led to redundancy through thicker walls and has resulted in wall thicknesses of rammed earth and cob structures between 300–500 mm. Conventional masonry structures typically use 90-100mm thick walls for internal partitions and the internal leaf of external walls. Adopting this thickness for unfired clay will overcome many barriers concerning the manufacture, construction and in-life use of the material. However, with a reduced wall thickness compared to typical earthen structures, there is reduced material redundancy and issues regarding high moisture contents arise again. To use unfired earth bricks require either a change in the way buildings are designed, constructed and habited, or the material needs to be enhanced to overcome the inherent low performance in elevated moisture conditions. Addressing this single issue, by creating low environmental impact bricks that have comparable performance and properties to current masonry units will negate many of the barriers.

1.2 Stabilised earth masonry

Soil stabilisation is a method of changing the inherent properties of soil to achieve improved properties. Many of the current methods were originally developed for ground stabilisation purposes but have been adapted for use in earthen construction. Inorganic methods of stabilisation typically involve the application of cement, lime and other hydraulic binders, as used throughout the concrete industry. The effect of the addition of these binders for rammed earth and compressed earth blocks is well documented (Parsons and Milburn, 2003; Reddy and Latha, 2013; Oti et al., 2009a) and this stabilisation can improve the strength, erosion resistance and dimensional stability. In addition to the methods used within concrete manufacture, inorganic stabilisers include the addition of any chemical compounds that are not based on hydrocarbons.

The addition of a chemical stabiliser will change the environmental impact of the unfired brick and potentially negating this benefit compared to alternative masonry units. While a full life cycle analysis is outside the scope of this paper, Maskell et al., (2014a) estimated the maximum stabiliser content based on the embodied energy and global warming potential compared with an Autoclaved Aerated Concrete (AAC), which was shown to have the lowest environmental impact of a range of typical masonry units. Based on this analysis, a maximum stabiliser content by mass of cement and lime was calculated to be approximately 8% and 7% respectively.

1.3 Inorganic stabilisation for extruded earth masonry

The focus of this paper is on the development of inorganic stabilisation methods that can be used with extruded unfired earth masonry units. The paper will investigate the addition of various mass fractions of cement and lime to a brick soil that is used for commercial fired brick production. Due to difficulties in full scale production, the laboratory scale production of small scale units developed by Maskell et al. (2013) was used. For the purposes of this paper, a successful stabilisation method is one that achieves a saturated or ‘wet’ unit compressive strength of 1MPa, without the reduction of a ‘dry’ compressive strength tested in ambient conditions. The mixing, extrusion and curing processes adopted in this study replicate those currently used in brick manufacturing plants in the UK. This approach was adopted to facilitate more rapid industry uptake.

2 Stabilisation mechanisms

2.1 Types of stabilisation

The three basic procedures of soil stabilisation are mechanical, physical and chemical (Houben and Guillaud, 1994). Mechanical stabilisation typically means compaction of the material to change the density and mechanical strength. Physical stabilisation involves texture change and can involve heat and electrical treatment. Chemical stabilisation is the result of reactions either between the soil and the stabiliser or a reaction within the stabiliser only.

The extrusion process within a brick manufacturing plant imparts distinct physical and mechanical properties to the bricks (Maskell et al., 2013). Without a substantial capital investment, additional mechanical and physical stabilisation would not be feasible. The commercial production of bricks in the UK is predominantly by the extrusion process (Bloodworth et al., 2001). Although a brick plant may be able to incorporate an alternative physical stabilisation process, except for currently drying and firing the bricks, this would be an additional process and likely incur a significant capital cost. Within the current process, soils are typically blended together, and liquid chemicals are currently added to the mix to aid in the firing process. Therefore, there is clearly scope for chemical stabilisation through the addition of either a powder or liquid prior to extrusion without significantly adding or changing current practices.

Potential mechanisms by which chemical stabilisation of the soil can occur have been summarised by Tingle and Santoni (2003) and include:

- Encapsulation of clay minerals;
- Cation exchange;
- Chemical breakdown of the clay;
- Absorption of organic molecules into the clay interlayer.

Various mass fractions of cement and lime could be added to the brick soil, which can then be extruded to achieve a stabilised brick. A review of the literature regarding the use of these stabilisers for other earthen constructions techniques is subsequently presented. Both cement and lime stabilisation are affected by curing temperatures and moisture conditions which affect hydration and other reaction rates, and these are discussed later.

2.2 Cement

The stabilisation mechanism of cement addition involves three processes including cation exchange, cementitious hydration and pozzolanic reactions (Prusinski and Bhattacharja, 1999). .The calcium silicate phases are regarded as more important in the stabilisation of soil (Prusinski and Bhattacharja, 1999). The hydration of these phases produces calcium hydroxide that provides the calcium ions for cation exchange. When Portland cement is mixed with materials with a high clay content cations within the double layer of the clay minerals are exchanged with the higher valence calcium ion, which causes a decrease in the double layer. This occurs immediately and results in an increased tendency to flocculate that leads to a agglomeration and a decrease in plasticity. The hydration of the cement produces the cementitious materials of Calcium Silica Hydrate (CSH) and Calcium Aluminia Hydrate (CAH). These hydrates encapsulate the clay particles and form strong bonds (Prusinski and Bhattacharja, 1999).

Tingle and Santoni (2003) tested the stabilising effect of American Type I cement on low plasticity soils with a Plastic Index (PI) of 13%. Although they were investigating the effects of non-traditional stabilisers, the cement stabilised soil was used as a basis of comparison. A 7% addition by dry weight of cement was found to reduce the Unconfined Compressive Strength (UCS) compared to an un-stabilised sample, with a 9% cement addition resulting in a UCS of 5.63 MPa; just a 6% increase. However, the beneficial effect of cement stabilisation under 'wet' conditions was demonstrated by Tingle and Santoni (2003). The 'wet' testing regime comprised of placing the samples in 25mm depth of water for 15 minutes. The procedure was developed to be more representative of actual conditions of unpaved roads. Under these conditions the UCS of un-stabilised samples decreased to 1.4 MPa. The UCS increased by 1.7 MPa and 3.0 MPa for the 7% and 9% cement mass fractions compared to the un-stabilised 'wet' sample.

Walker (2004) tested CEB stabilised with 5% cement under more severe testing conditions. The soil with an 11% clay fraction had a LL of 19% and a PI of 7% with kaolin identified as the clay mineral present. The sample achieved a minimum dry compressive strength of 8.5 MPa which when submerged in water for 24 hours reduced to 3.9 MPa.

2.3 Lime

The mechanism by which lime can stabilise a soil is relatively well understood. Two separate reactions occur, cation exchange and pozzolanic reactions, that are similar to the mechanisms of cement stabilisation discussed above. Greaves (1996) includes an initial drying out mechanism by an absorption and evaporation. Quicklime (Calcium Oxide) or hydrated lime (Calcium Hydroxide ($Ca(OH)_2$)) both provide a source of calcium that is required for soil stabilisation. Quicklime would absorb water from the surrounding soil to form hydrated lime. This slaking reaction is exothermic and the heat generated may cause further loss of water by evaporation (Rogers and Glendinning, 1996). Immediately after the lime is added to the soil, cation exchange occurs, exchanging calcium ions from the lime with metal ions within the clay mineral (Greaves, 1996). Rogers and Glendinning (1996) comment on the observed changes and the effect on the engineering properties. This includes reduction of the double layer and flocculation, which increases the Plastic Limit (PL) and thereby reducing the PI. This has clear implications for extrusion that is typically undertaken at the PL Maskell et al., (2013)

Clay minerals react with lime to form a cementitious material over a longer period of time. The lime causes the pH level to rise which causes the silica and alluminia sheets of the clay minerals to partially dissolve and react with calcium to form CSH and CAH (Prusinski and Bhattacharja, 1999). These crystallise to form a matrix of cementitious material that binds the particles together. The partial incorporation of the clay minerals into the cementitious matrix by the use of lime, compared to the encapsulation by cement has been observed through XRD by Reddy and Latha (2013).

Rafalko et al. (2007) comments that for maximum strength increase there is an optimum amount of lime that can be added which is dependent on the clay mineralogy. An increase in the amount of lime added causes a decrease in dry density and a reduction in strength. The effect after three days of 5% addition of pelletised quicklime to two clays both classified as high plasticity clays was also studied. The addition of the lime to the 45% kaolinite and 20% montmorillonite soil showed an increase in UCS from 0.11 to 0.76 MPa, whereas a greater increase was measured with a 10% kaolinite and 60% montmorillonite soil. Although the measured UCS of the soil was low, the tests show the relative strength improvement of lime and the variability depending on clay mineralogy.

Although not directly comparable, Tingle and Santoni (2003) added three different percentages of hydraulic lime to high and low plasticity soils. Since the plasticity of soils is inherently related to clay mineralogy (Bain, 1971), the addition of lime can be compared to the addition of cement as mentioned previously. Addition of 3, 5 and 7% hydraulic lime resulted in a reduction of UCS in both samples. This was most severe with the high plasticity soil where a 7% addition resulted in a UCS of 1.02 MPa, approximately 21% of the strength of an unstabilised sample.

2.4 Summary

While the use of cement and lime for chemical stabilisation is relatively common for earthen construction, its use with extruded earth bricks is limited. The performance of these stabilisers is dependent on the properties of the soil, which for extruded bricks has been shown by both Heath et al. (2009) and Maskell et al. (2013) to be different to other forms of earthen construction. This paper will allow for the comparison extruded bricks stabilised with cement and lime with other forms.

3 Materials and Methods

3.1 Materials

Heath et al. (2009) demonstrated that the soil used for fired bricks was suitable for unfired clay bricks, with Maskell (2013) demonstrating the range in physical and chemical properties of brick soils. Whilst a range of properties was observed, bricks soils can be classified as predominantly silt sized with the behaviour of a low plasticity clay. Due to the variability of the material used, it was infeasible to investigate the effect of cement and lime on all the brick soils, so only a single soil was chosen. Based on the analysis of a number of different brick soils, the chosen soil is representative of the range used for commercial fired brick manufacture in the UK, based on its particle size distribution, plasticity and mineralogy. This ensures that a successful method of stabilisation with this single soil is more likely to be suitable for other brick soils. The physical properties and mineral content of the chosen soil was investigated by Maskell et al. (2013) and is represented in Table 1. The soil can be described as dark brown sandy silt, with a plasticity classification corresponding to a low plasticity clay (BS 5930:1999, 2010). As presented by Maskell et al. (2013), the mineralogy and chemical composition of the soil was determined by X-ray diffraction (XRD), as in Figure 1, and X-ray Fluorescence analysis, as in Table 1. Only the five main metal oxides are presented along with the Loss On Ignition (LOI).

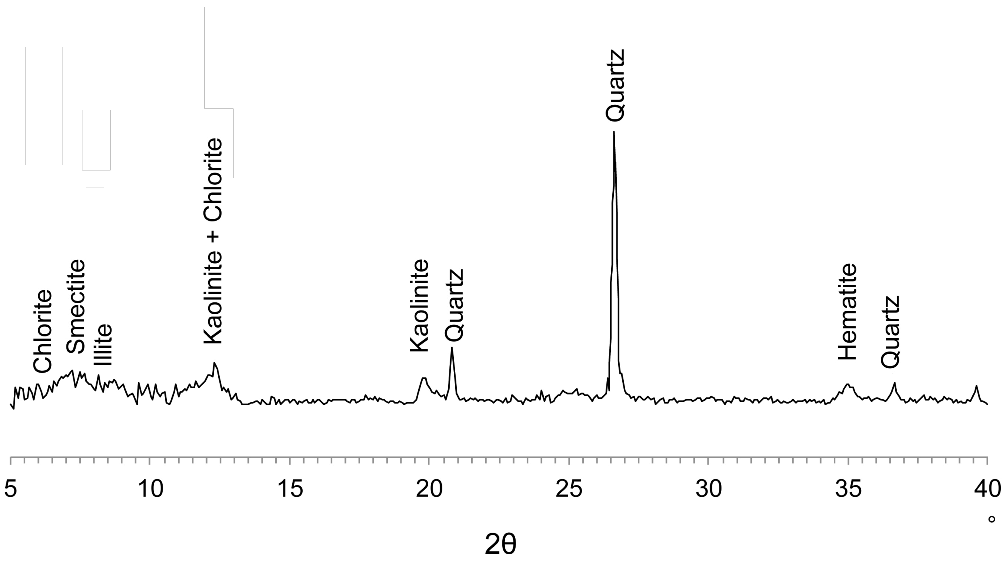

Figure 1: XRD of Brick Soil

Table 1: Soil Properties (Maskell et al., 2013)

Properties	%
Physical Properties	
Liquid Limit	24
Plasticity Index	8
Linear Shrinkage	6
Particle Grading	
Sand	33
Silt	46
Clay	16
Mineral Content	
Siderite	2
Hematite	3
Smectite	3
Chlorite	6
Illite	16
Kaolinite	31
Quartz	39

Oxide Composition (wt.)	
SiO_2	57.48
Al_2O_3	17.04
Fe_2O_3	11.36
K_2O	3.72
TiO_2	1.36
LOI	7.4

3.2 Sample Preparation

Scaled bricks were manufactured within a laboratory environment at the University of Bath, using a small-scale bench top vacuum extruder as shown in Fig. 2. It is infeasible to manufacture full-scale bricks in a laboratory, therefore bricks at 1:3 linear scale (1:27 volumetric scale) were produced as shown in Fig. 3. These bricks measured nominally 72 mm by 34 mm by 22 mm thick. Maskell et al., (2013) demonstrated the feasibility of using the small-scale extruder for the manufacture of representative full scale bricks for compressive strength testing.

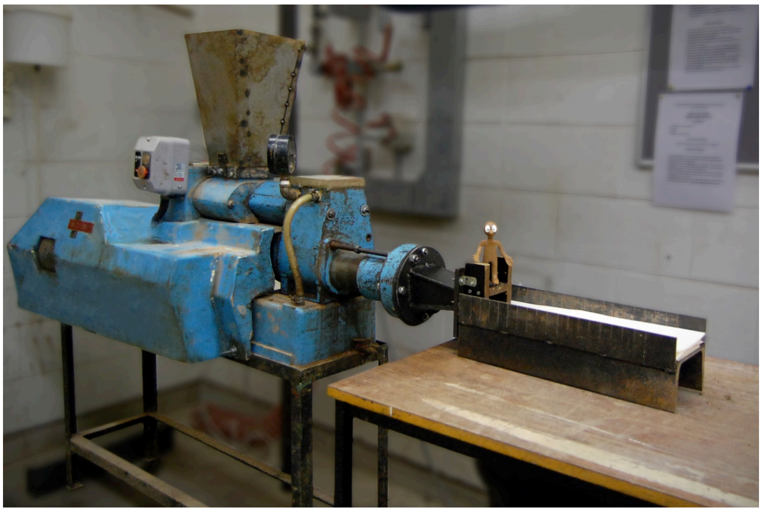

Figure 2: Small scale extruder

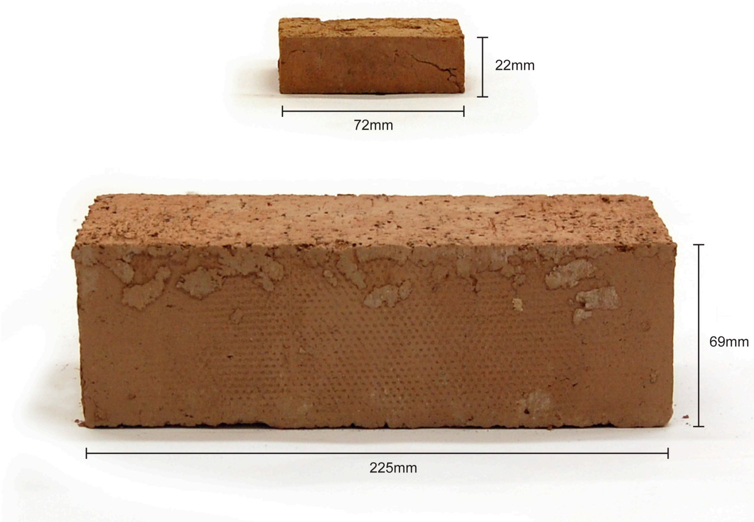

Figure 3: Full size and small scale extruded earth bricks.

3.3 Experimental Testing Methods

In addition to the chemical and physical properties of soil, there are many dependent variables on the successful application of a stabiliser. These include the effect of stabiliser type, stabiliser mass fraction, curing regime and curing time. These variables are likely to affect the density and Moisture Content (MC) of the specimens that are likely to affect the compressive strength of the units. Prusinski and Bhattacharja (1999) discuss the effect that the addition of stabilisers has on the engineering properties, noting that the plasticity properties show considerable changes. The ability of the material to be extruded is dependent on the plasticity of the soil and therefore the MC of the soil. While this has been defined for the unstabilised specimens, the PL is likely to change with cement or lime stabilisation. Therefore the Extrusion Moisture Content (EMC) will be considered, which is a measure of the MC of material following extrusion and so represents the MC that the soil can be extruded at.

Varying the curing regime will investigate if any stabilisation effect would be facilitated or accelerated through an initially elevated temperature. Each of these factors may influence the strength development over time. All of the bricks were air dried in a conditioning room (average of 20 °C at 61% relative humidity) for two days, followed by varied drying procedure according to the experimental requirement. Random brick samples were dried in the conditioning room while the drying of other bricks was accelerated; one sample of bricks was artificially dried in an oven at 60 °C with another sample dried at 105 °C. Commercial bricks are dried pre-firing in an oven, often at 60 °C, while drying at 105 °C would typically lead to the complete removal of unbound moisture from the specimen. Although there was initially considerably more moisture available for hydration than in typical concretes (water : cement or lime ratio of between 2.1 and 6.0, depending on particular max and stabiliser content) the heat curing could result in insufficient moisture for hydration or other reactions, as discussed later. While curing can include the addition of moisture to facilitate hydration processes, this has not been investigated as there is no current moist curing for commercial fired bricks and as mentioned earlier, an aim was to ensure the mixing, extrusion and curing was according to existing processes in a brick plant. Following two days within the ovens, the specimens were removed and stored within the laboratory until testing. To investigate the development of strength, bricks were tested at 7, 14 and 28 days.

The conditioning of specimens before testing should be comparable to the current methodology adopted for standard masonry units. Compression testing of all these specimens occurred. Specimens had been conditioned according to §7.3.2 and §7.3.5 of BS EN 772-1:2000 (2000). This stipulates that one sample of specimens be air dried while the other samples are fully immersed in distilled water for no less than 16 hours prior to testing. These represent testing the specimens 'dry' and 'wet' respectively. The specimens remained uncapped during compression testing, as Maskell et al., (2013) showed there was no significant variation from capping small-scale specimens. The compressive strength results presented are not normalised for the sample dimensions as in Annex A of BS EN 772-1:2000 (2000).

There is a complex interaction between stabiliser, stabiliser mass fraction, EMC, Initial Curing Temperature (ICT) and curing time that produces different dry densities and moisture contents which will affect the strength.. Six samples of each group were tested, this allows for analysis based on the averages and variance to be undertaken.

4 Results and Discussion

The following section presents the individual results of the variation in stabiliser (cement / lime or unstabilised control), stabiliser mass fraction and ICT. A discussion comparing the cement and lime stabilisation of extruded earth bricks follows.

4.1 Unstabilised

Unstabilised bricks were extruded and used as a control to quantitatively assess the relative performance of either the addition of cement and lime. The bricks were extruded at an average moisture content of 15.6% and had an average dry density of 1950kg/m^3. There was no significant variation in these measurements between the different tests with the Coefficient of Variation (CV) for the moisture content and the density being 2.5% and 4.6% respectively. The compressive strength is statistically independent of these variables within the limited range of density and moisture and shown in Table 2.

Table 2: Unstabilised Compressive Strength Results

Days Since Extrusion	Initial curing temperature °C	Compressive strength MPa
14	20	3.17
	60	3.19
	105	3.39
28	20	3.24
	60	3.33
	105	3.39

4.2 Cement

The mixture was prepared by first dry mixing CEM II 52.5 N cement with the soil. Distilled water was then slowly added into this dry mix and subsequently mixed for a further ten minutes. The cement stabilised bricks were extruded at an average EMC of 17.6% with insignificant variation respective of the mass fraction used. The average dry density of all the cement stabilised small-scale bricks tested was 1867kg/m^3 with a CV of 8.25%. The results of the compression tests on the cement stabilised small scale brick specimens are presented in Fig 4, with error bars indicating the 95% confidence interval.

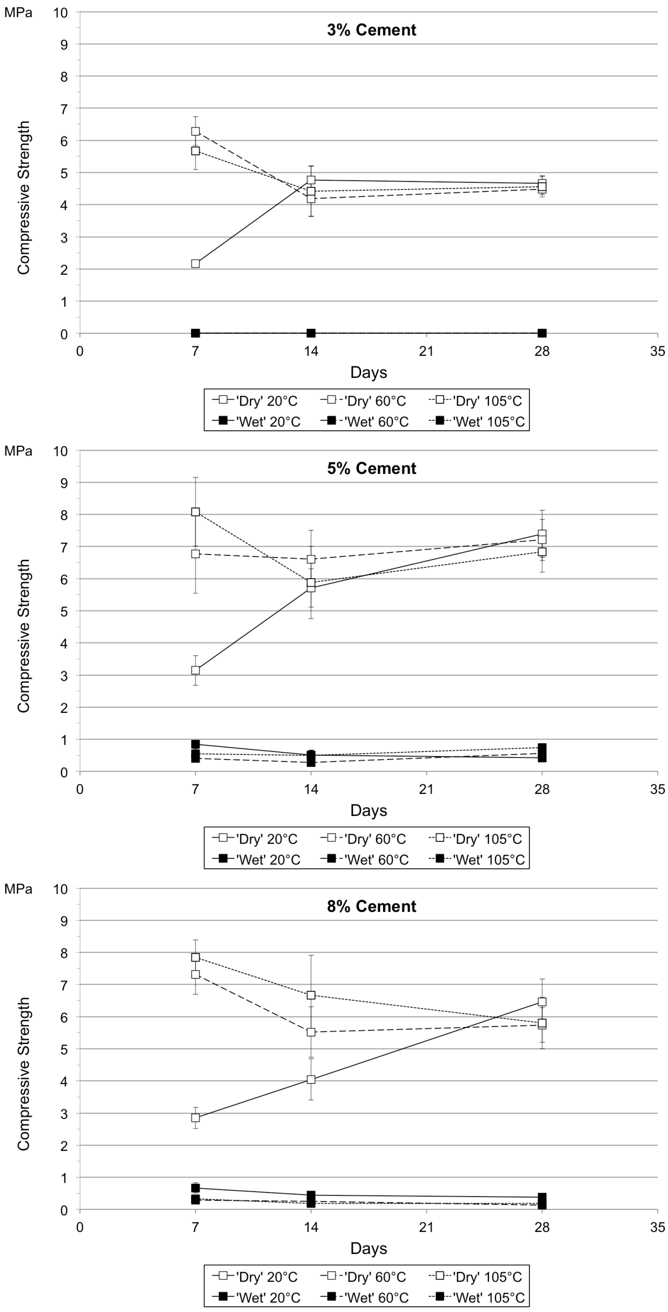

Figure 4: 3, 5 and 8% cement stabilised compressive strength results

The maximum 'dry' compressive strength of the small scale bricks achieved was 7.4MPa with the addition of 5% cement and cured at 20°C. The maximum 'wet' compressive strength of the small-scale bricks was 10% of the 'dry' strength, achieving 0.74 MPa with the addition of 5% cement and cured at 105 °C. There is a change in strength over time, which is dependent on the ICT with samples moving towards an equilibrium moisture content. The MC of the samples cured at 20 °C, on average decreased by 5.87% from 7 to 14 days while the MC of the samples cured at 105 °C increased by 0.65% over the same time period. Along with the manipulated hydration mechanisms, this change is MC would have resulted in a change in strength in accordance with Jaquin et al., (2009) and Heath et al., (2009). From 14 days, there is no statistical significant difference in compressive strength due to change in initial curing condition based on the two-tail t test.

While the samples that had been cured initially at 105 °C increased in strength with increasing mass fraction of cement there is only a 4% increase in 'dry' compressive strength between 5 and 8% addition. There is only 0.05MPa difference in 'wet' strength for the different ICTs, but in contrast to the 'dry' specimens there is a 0.65MPa increase in strength between 5 and 8% addition. Although the small-scale brick specimens show an apparent optimum cement content of 5%, a two-tail t test shows there is no significant difference in 'dry' strength between the addition of 5% and 8% cement. While statistically there is not an increase in strength with an increase in mass fraction from 5% to 8%, this lack of change is in contrast to work presented by Tingle and Santoni (2003), Walker (2004) and Reddy and Gupta (2006) that showed increasing strength with respect to increasing cement mass fraction, but this is consistent with Minke (2006). This confirms that the use of stabilisation methods developed for compressed earth blocks or rammed earth may not be applicable to extruded earth.

4.3 Lime

The mixture was prepared before extrusion by first dry mixing hydrated lime with the soil. Distilled water was then added into this dry mix and subsequently mixed for a further ten minutes. The results of the compression tests on the lime stabilised small scale brick specimens are presented in Figs. 5, with error bars indicating the 95% confidence interval. The average dry density of all the lime stabilised small scale bricks tested was 1764 kg/m^3 with a CV of 3.83%.

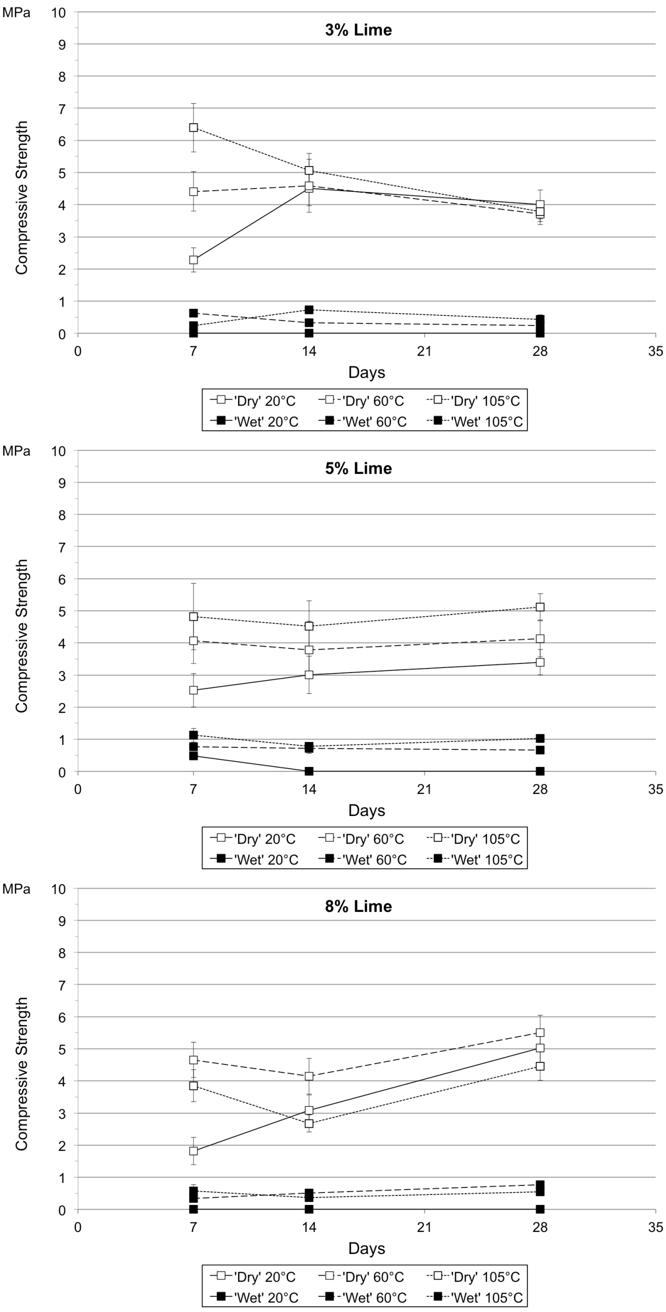

Figure 5: 3, 5 and 8% lime stabilised compressive strength results

All the specimens achieved a greater compressive strength than the CEBs tested by Oti et al. (2008b) that achieved 0.69 MPa with a 20% addition of quicklime, CaO, which is equivalent to 26% of the hydrated lime used in this study. The specimens for this current study, which were initially cured at 105°C, showed an apparent optimum 'dry' and 'wet' strength at 28 days with a 5% lime addition, with the other ICTs achieving the greatest strength achieved with 8% mass fraction. Rafalko et al. (2007) comments that there is an optimum mass fraction of lime for soil stabilisation, which has not been observed within this range. Regardless of mass fraction used, no samples initially cured at 20 °C achieved a measurable 'wet' strength. Fig. 5 indicates that small scale bricks with 3% lime addition are unaffected by the ICT at 28 days. The samples with a 5% lime addition indicate that compressive strength increases with increasing ICT, while the 8% addition of lime indicates that there is an apparent optimum curing temperature.

The initial change in strength with respect to time is similar to the unstabilised and cement stabilsied samples, which is dependent on the initial curing condition. The MC of the samples cured at 20 °C, on average decreased by 0.84% from 7 to 14 days while the MC of the samples cured at 105 °C increased by 0.64% over the same time period. From 14 days there is a further increase in strength for the small-scale bricks stabilised with the addition of 5 and 8% lime. Comparing the two, only the 28 day strength of the 8% lime stabilised is statistically greater than the 14 day strength, based on the one-tail t test, with the 5% addition showing although the mean strength increases from 14 to 28 days, this increase is not significant at the 95% confidence level.

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4.4 Influence of stabilisers in strength performance

Two stabilisers, used in varying mass fractions, cured at three different temperature regimes were investigated. This created 18 different specimen groups, that were tested both 'dry' and 'wet' at 7, 14 and 28 days. With six replicates of each, this represents a total of 648 small-scale bricks tested. This section compares physical and mechanical performance of the cement and lime stabilised specimens.

The effect of mass fraction of stabiliser on the 28 day compressive is presented in Fig. 6, with error bars indicating the 95% confidence interval. The range of stabilised compressive strength achieved was from 3.40 to 7.40 MPa. All 18 of the specimens groups achieved greater 'dry' compressive strength than the equivalent unstabilised specimens. Based on the one-tail t test an additional six stabilised samples, presented in Table 3, were not statistically different from the unstabilised specimens with the equivalent ICT.

Table 2: p-values of samples not statistically different from equivalent unstabilised samples

Stabiliser	Stabiliser mass fraction %	ICT °C	p-value
Cement	8	105	0.051
Lime	3	60	0.293
Lime	3	105	0.295
Lime	5	20	0.069
Lime	5	60	0.052
Lime	8	105	0.062

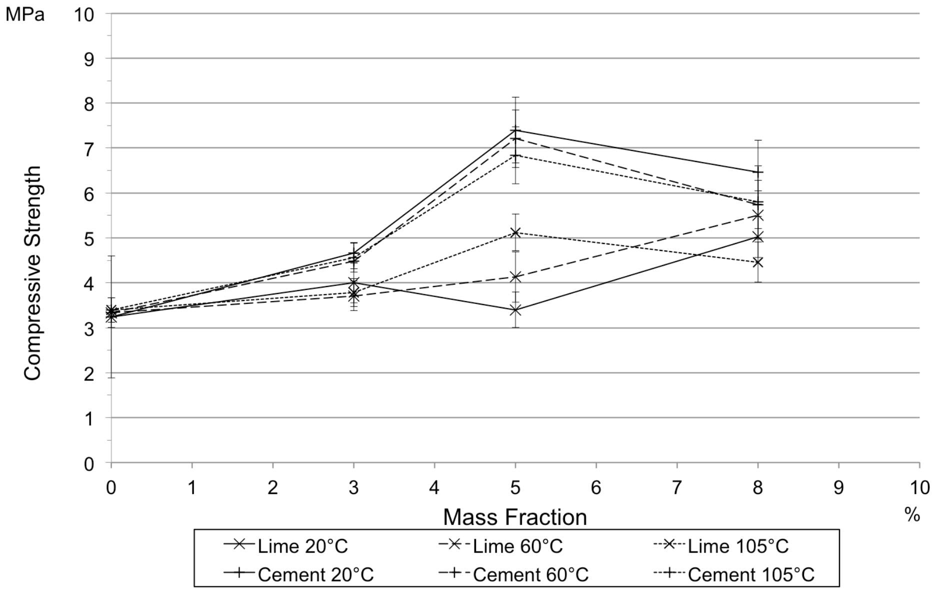

Figure 6: 28 Day 'dry' strength for various stabilisers cured at 20, 60 and 105°C

The EMC was determined based on the workability of the mixture and its ability to be extruded. The effect of extruding the bricks with the addition of the stabilisers discussed is presented in Fig. 7. Each data point represents the average of nine sample group dry densities measurements at 7, 14 and 28 days for the different ICT. Each sample are an average of six brick specimens; representing average of 54 measurements. Included are error bars representing the 95% confidence interval of the mean, based on the 9 group densities. There is a clear relationship between EMC and dry density of the bricks as noted for compaction of clay soils above the optimum water content (Seed and Chan, 1959).

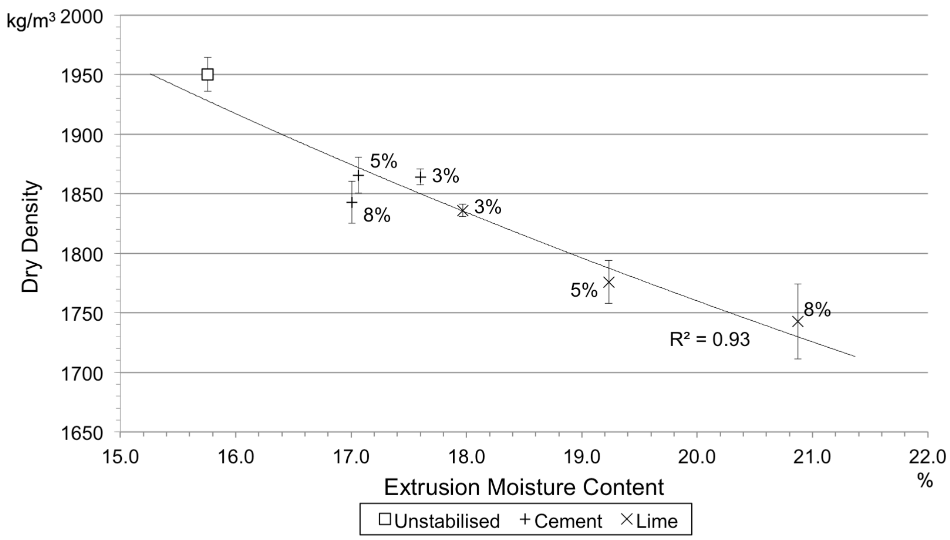

Figure 7: Relationship between extrusion moisture content and dry density

Earthen construction methods achieve a greater compressive strength increasing the density. The influence of dry on the compressive strength of the samples is illustrated in Figure 8. When the specimen is stabilised the effect of density on the strength is negligible, as confirmed by multiple non-linear regression. In addition to density strength of unstabilised samples is dependent on the MC at the time of testing (Jaquin et al., 2009 and Heath et al., 2009). There is no relationship between strength and MC (Figure 9) of the stabilised samples when the stabilisation method is not considered which is confirmed by multiple non-linear regression.

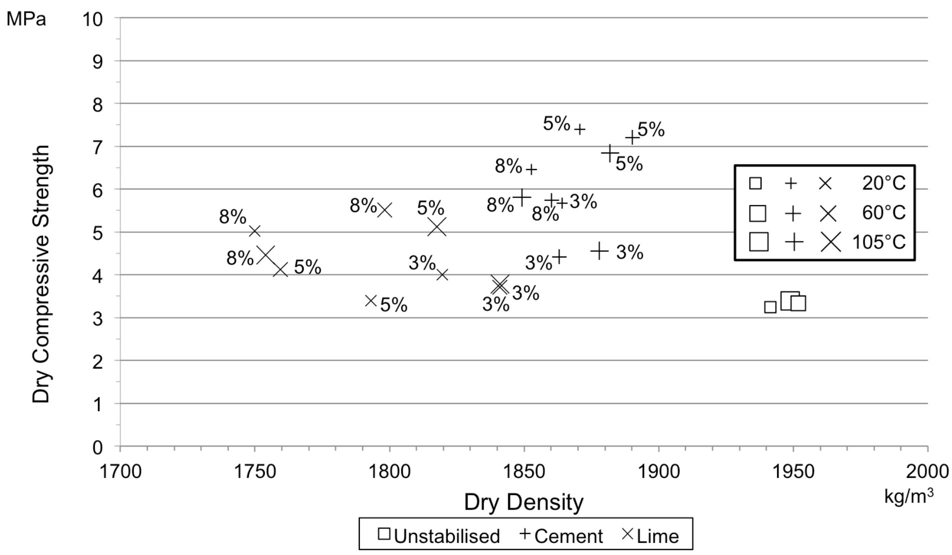

Figure 8: 28 Day relationship between density and dry strength

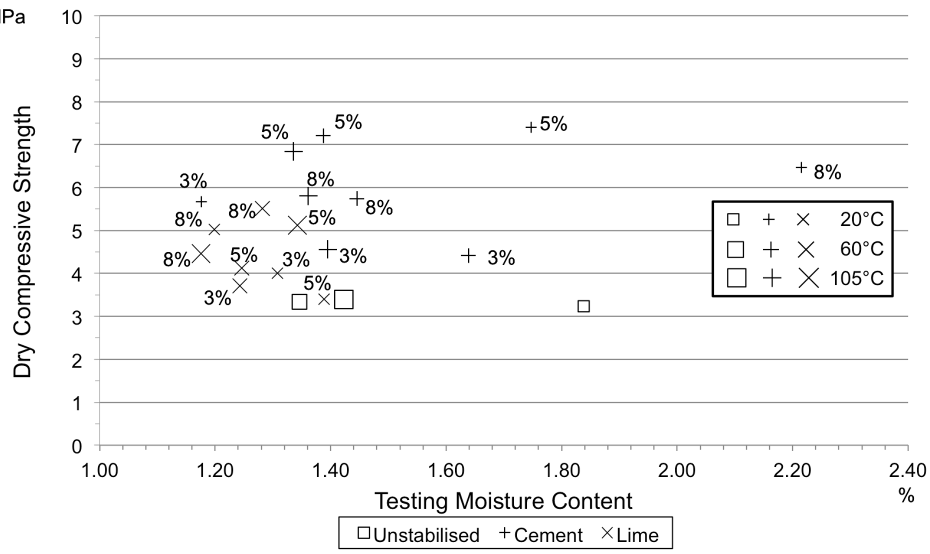

Figure 9: 28 Day relationship between moisture content and dry strength

These results, confirmed by ANOVA, show that the interaction of the variables: stabiliser, stabiliser mass fraction and ICT are significant with respect to stabilised specimen dry compressive strength gain. While for unstabilised specimens the physical properties, such as density and moisture content, dominate the influence for dry compressive strength. The addition of stabilisers will affect the physical and mechanical properties and their inter-relationship resulting from the manufacturing process of bricks. If the plasticity properties were altered this would effect the workability and this change would be reflected in the mechanical properties of the brick.. An industrial extruder is able to accommodate these changes to a greater extent and achieve greater extrusion pressures enabling a lower EMC, though this may lead to increased operational and maintenance cost.

The development of strength with time for the varying stabilisers, as presented in Figures 4 and 5. The 'wet' compressive strength of the specimens did not significantly vary over 7, 14 and 28 days, while the specimens tested 'dry' generally showed greater variation in strength development. The strength development is largely dependent on the ICT of the specimens, with a large of variation in 'dry' strength at 7 days due to the ICT.

The relationship between the ICT and early age strength development of the 'dry' specimens is partially attributed to the effect an elevated temperature has on the MC of the specimens, an effect that also depends on the EMC. The testing MC is generally higher for the specimens without an elevated ICT, as seen in Figure 9, while the MC of the specimens cured at either 60 °C or 105 °C are almost identical. In accordance with Maskell et al., (2013) the moisture within the various stabilised specimens changes over to time and moves towards an equilibrium, regardless of ICT.

4.5 Discussion of stabilisation

There will be continuing hydration and carbonation reactions occurring within the cement and lime specimens. Oti et al. (2009a) showed that strength for cement and lime stabilised CEBs will continue to increase for up to 90 days. There is an inherent difficulty in comparing unstabilised earthen construction due to the variability of the soil type and the method of production. The addition of a stabiliser compounds this effect, especially considering that each stabiliser reacts differently with the physiochemical properties of the earth, with multiple variables interacting. Tingle and Santoni (2003) tested both cement and lime at various mass fractions and while the relative 'dry' compressive strength is in agreement with the results presented here, Tingle and Santoni (2003) also found that cement performs better under 'wet' conditions which is in contrast to the findings presented here.

The requirement for a stabilised unit has been set to at least maintain the equivalent strength of an unstabilised equivalent at approximately 3.2 MPa with the other criterion being a minimum 'wet' compressive strength of 1.0MPa. Only 12 of the 18 stabilised specimen groups tested at 28 days were able to be measured following full submersion. The results as compared to the equivalent 'dry' strengths are shown in Fig. 10, with error bars indicating the 95% confidence interval. There is an apparent relationship between the 'dry' and 'wet' strengths for the specific stabiliser, providing that the 'wet' bricks can be measured. This implies that the fundamental mechanism of strength development by stabilisation differs between the various stabilisers, as expected from the literature.

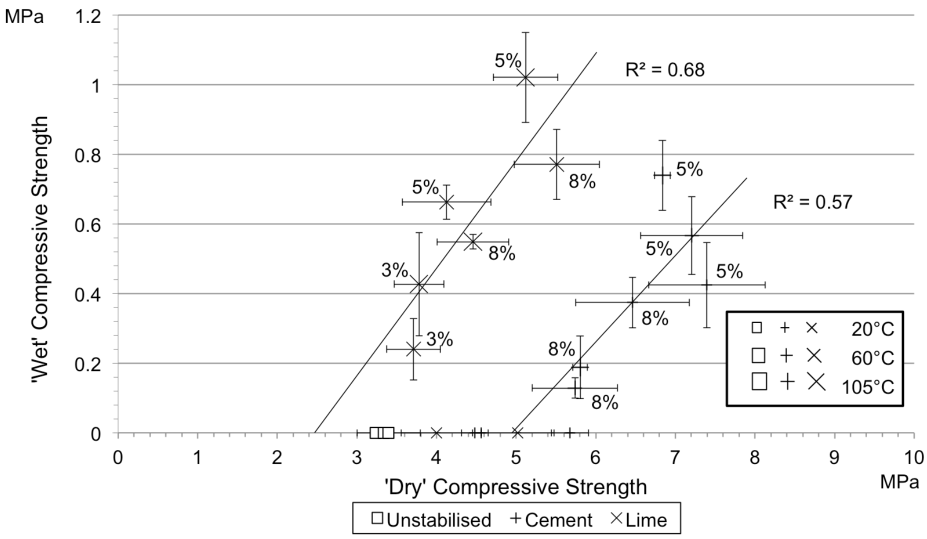

Figure 7: 28 Day relationship between 'dry' and 'wet' strength for various stabilisers

While the pozzoloanic reactions that occur in cement are advantageous for dry strength compared to lime, the lime specimens achieved a greater relative improvement in wet strength. The improvement can be attributed to the involvement of the clay mineralogy in the pozzolanic reactions when lime is used as observed by Reddy and Latha (2013). Although encapsulation of the minerals results in a greater dry compressive strength, due to the drop of strength under 'wet' conditions, it is assumed that only partial encapsulation was achieved. Full saturation of the units removed the pore suction and led to a particulate suspension with the partial encapsulation of the clay minerals insufficient to prevent the suspension. As the pozzolanic reactions due to the presence of lime incorporates the clay mineralogy, weaker bonds within the overall matrix exist resulting in the lower 'dry' compressive strength. However, the interaction mechanism and inclusion of the clay minerals within the matrix allowed for a greater 'wet' compressive strength. While XRD has been used to show the relative reactions occurring and the change is spectra peaks (Reddy and Latha, 2012), it is difficult to show the uniformity of this effect, even with Scanning Electron Microscope techniques (Oti et al., 2009a).

The specimen with the addition of 5% lime that was initially cured at 105°C achieved the greatest average 'wet' compressive strength. Due to the variation in the six readings of the 'wet' strength, the 95% confidence interval of the true strength is 0.89 to 1.15 MPa. This indicates that although the sample mean may be suitable for structural applications (Heath et al, 2012), there remains concerns over the suitability of the use of cement and lime for stabilising extruded earth masonry units. Therefore, these methods of stabilisation could be deemed as unsuccessful, due to no mechanism achieving the desired 'wet' strength performance.

5 Summary

This paper has presented results from testing on stabilised soil specimens. Small-scale brick samples were stabilised with cement and lime and tested in compression under wet and dry conditions for a measure of the stabilisation effectiveness.

All stabilisers showed potential to increase strength, but it was observed that there is little relationship with respect to the dry compressive strength performance when considering a generic stabilised specimen to an unstabilised specimen, without consideration of whether cement or lime was used. The effect of a chemical addition changes the workability of the mixes, which has been expressed as the EMC. This changes the resulting dry density that can be achieved. The MC at testing is a result of the combination of stabiliser, stabiliser mass fraction, EMC and time since extrusion. The dry density and MC seemingly have little impact on dry compressive strength after stabilisation with either cement or lime.

Considering the stabilisers separately, the MC in each of the stabilisers has an effect on the strength achieved. Cement and lime, were added in mass fractions ranging from 3 to 8%. There is an apparent optimum cement mass fraction while the compressive strength of lime increases with increasing mass fraction within this range. Varying the ICTs has shown to have some effect with these stabilisers, particularly in achieving early age strength.

While the majority of stabilisation methods that were tested increased the 'dry' compressive strength, there was greater variability with respect to improvement in 'wet' compressive strength. Only the specimen with the addition of 5% lime that was initial cured at 105 °C achieved an average 'wet' compressive strength greater 1 MPa. Different properties may be achieved with the addition of alternative stabilisers or with the modification of the soil, but these may affect the extrusion process. Alternatively, secondary stabilisers could be included in addition to the primary stabilisers investigated here. This will help to ensure extruded unfired bricks can be used within loading bearing structural systems with confidence over their integrity under severe conditions.

This research has shown that the stabilisation process for extruded clay masonry units is different to that for compressed earth blocks and other forms of earth construction. Further research into alternative stabilisers is required to produce unfired clay masonry units, which have the lowest possible environmental impacts.

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